JLab detector and IR

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for JLab's MEIC Study Group

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Jefferson Lab
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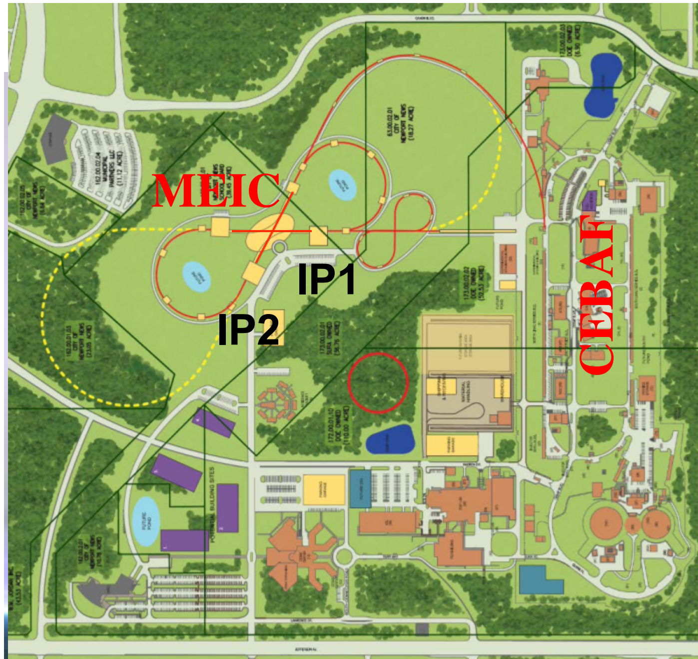
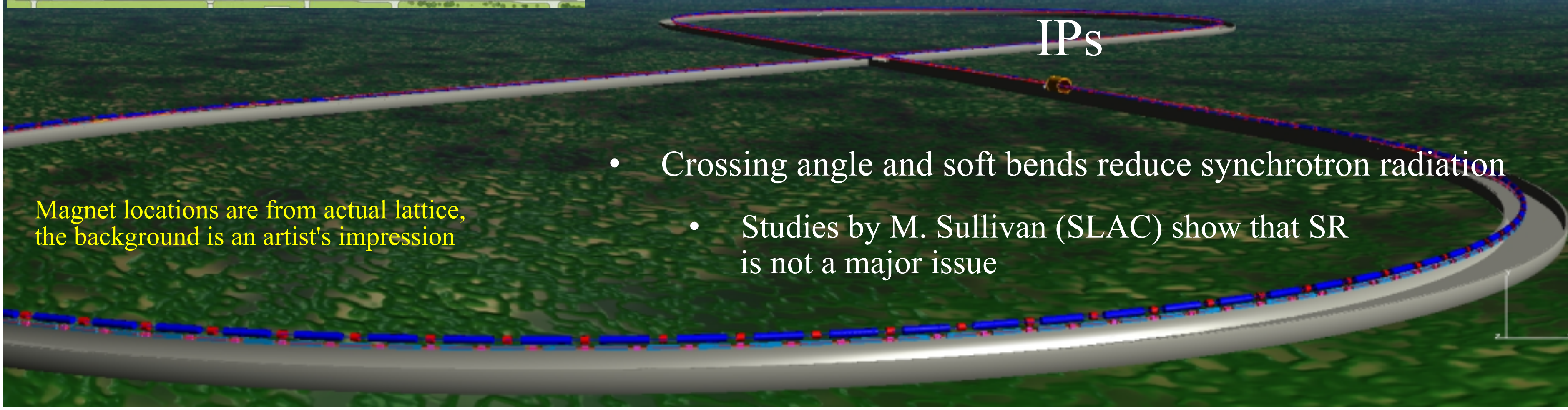
Outline

- Introduction
- Central detector
  - Solenoid options
  - Priorities
- Extended interaction region and detector integration
  - Small-angle detection of hadrons and nuclear fragments
  - Low-Q^2 (electron) tagger
- Bunch identification and trigger
- Generic Detector R&D for an EIC

Detector locations and backgrounds



- IP locations reduce synchrotron- and hadronic backgrounds
  - *Far* from arc where electrons exit (synchrotron)
  - *Close* to arc where ions exit (hadronic)
- Scaling from HERA (pp cross section, multiplicity, current) suggest comparable hadronic background at similar vacuum
  - Should be possible to reach better vacuum (early HERA: 10^{-7} torr, LHC goal: 10^{-10} torr)
  - MEIC luminosity is more than 100 times higher
  - *Signal-to-background (random hadronic)* should be 10^{3}-10^{4} times better



Magnet locations are from actual lattice, the background is an artist's impression

- Crossing angle and soft bends reduce synchrotron radiation
  - Studies by M. Sullivan (SLAC) show that SR is not a major issue

Detector development overview

- Central Detector – evolutionary
  - Basic requirements and technologies/solutions understood
  - Need to optimize performance and cost of subsystems
  - When possible, use innovative design features (large crossing angle, dual solenoid) to relax specs and/or improve performance
  - Important to explore full phase space of technologies/configurations
  - Ultimately, we would want to have two complementary detectors

    At the MEIC both can run simultaneously without beam time sharing

- Small-angle hadron and electron detection – new opportunities
  - Accelerator integration is the highest priority since it allows the storage ring to be designed around the detector needs
  - Novel design allows reaching unprecedented acceptance and resolution

- Detector R&D – in collaboration with BNL
  - Most detector technologies can be applied both at JLab and BNL
  - The Generic Detector R&D for an EIC program is good for bringing together people at the labs and in the two user communities

Central detector solenoid options

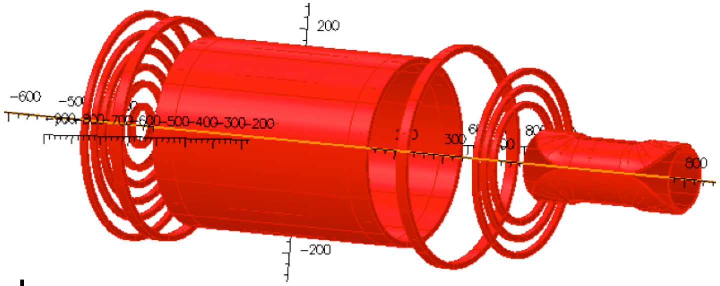
- Existing magnets
  - The CLEO and BaBar would be suitable for use in the MEIC at either IP
  - The magnets are very similar:

    4 m long, 3 m diameter, 1.5 T field, iron yoke
  - In the near term it is planned to use the CLEO magnet for SoLID at JLab, and BaBar for an upgrade to PHENIX at BNL

    Both should be in good condition and available for use in the EIC

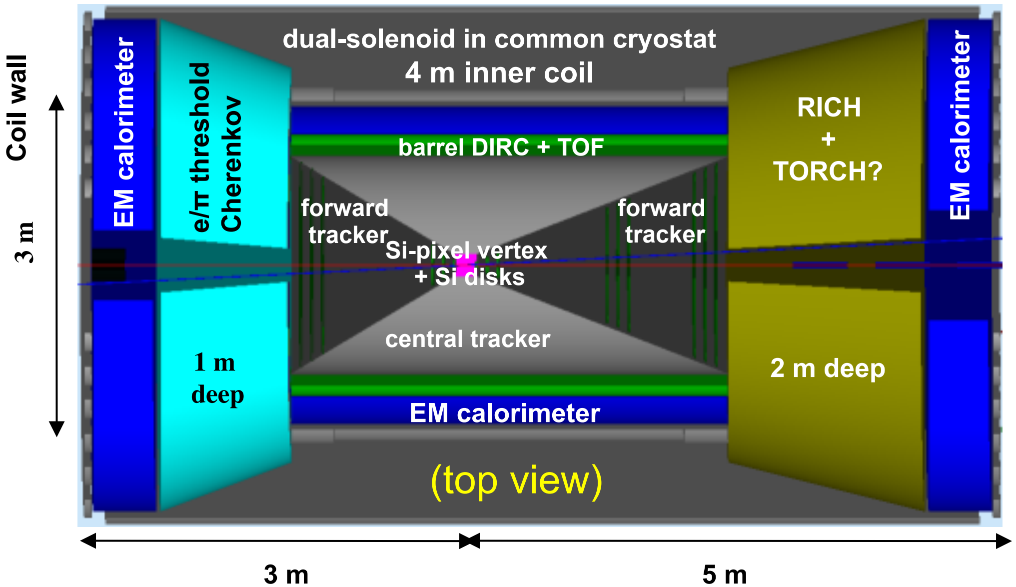
- Option: iron-free dual solenoid for IP1
  - Inner and outer solenoids have opposite polarity

    Space in-between provides an iron-free flux return
  - Proposed for the ILC 4th detector concept
  - **Advantages:** light weight, high field (3 T), improved endcap acceptance, compact endcaps (coils instead of iron), easy detector access, low external field, precise internal field map (no hysteresis)
  - Ideal for a detector optimized for SIDIS and exclusive processes
  - Initial (magnetic) design is ready



TOSCA model of the dual solenoid showing inner solenoid, shaping coils, endcap coils, and one possible version of the forward dipole. The outer solenoid is not shown.

Central detector design



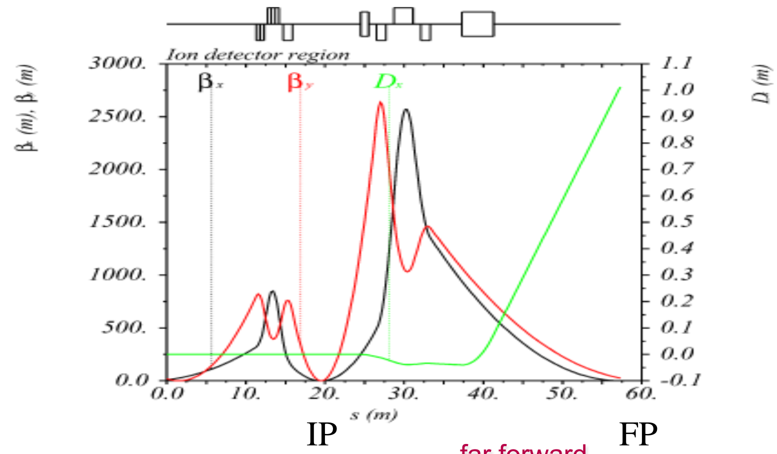
- Dual-solenoid-based detector in GEMC (a GEANT4 package also used for JLab 12 GeV)
- Configuration shown with forward- and central trackers based on micropattern gas detectors (GEM/micromegas).
- Central tracker could also include a low-mass, cluster-counting, He-filled drift chamber (ILC 4^{th} concept).

- **Primary focus:** One detector compatible with the full-acceptance interaction region, optimized for SIDIS and exclusive reactions
- Current tracker layout is compatible with both a dual solenoid and the CLEO magnet (but the latter would restrict the endcaps)
- A 2^{nd} detector could use a TPC and focus on hadronic calorimetry (jets)
- An explicit design of the 2^{nd} IR will begin soon.

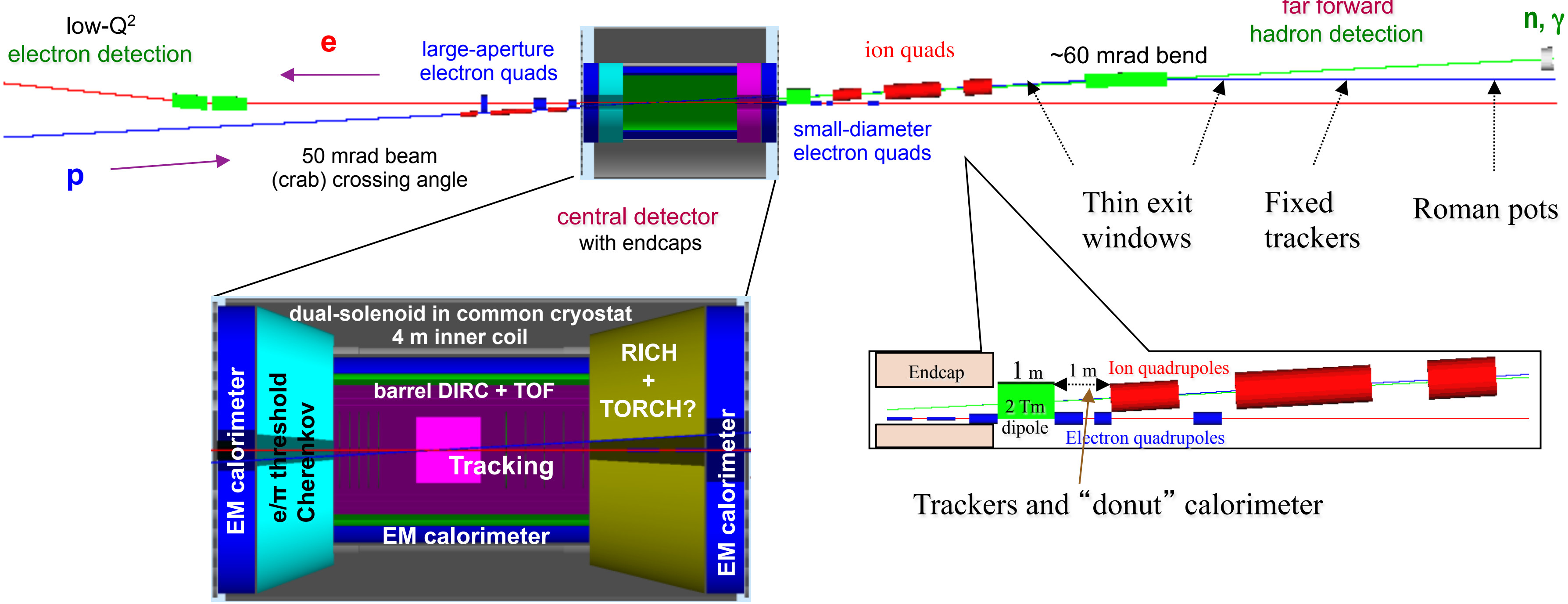
The MEIC *full-acceptance* detector

Design goals:

1. **Detection/identification of complete final state**
2. **Spectator p_T resolution << Fermi momentum**
3. **Low-Q^2 electron tagger for photoproduction**

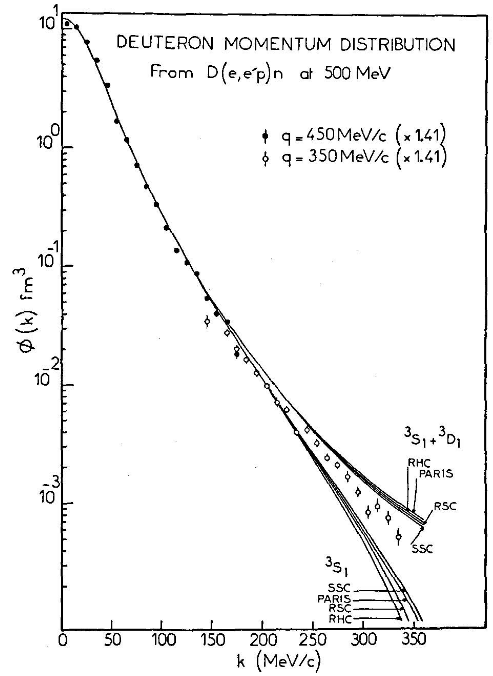


(from GEANT4, top view)

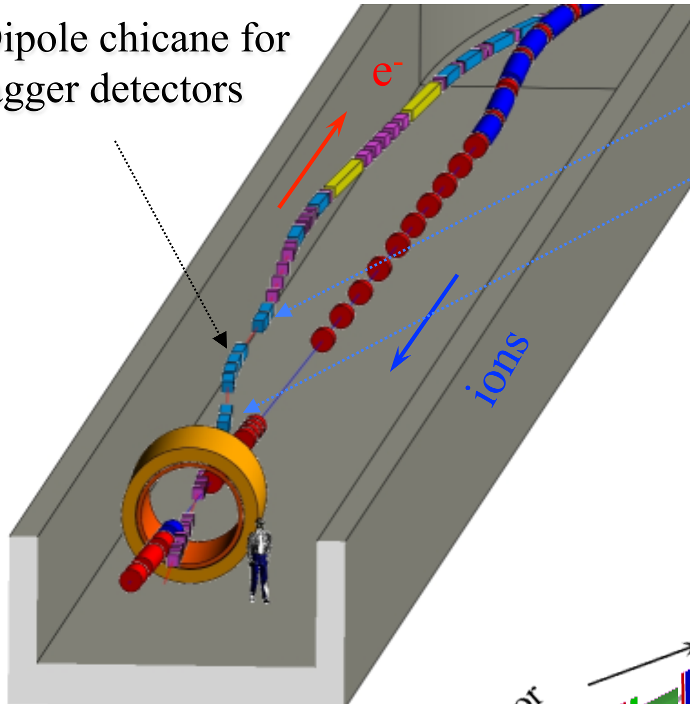


Forward detection – processes

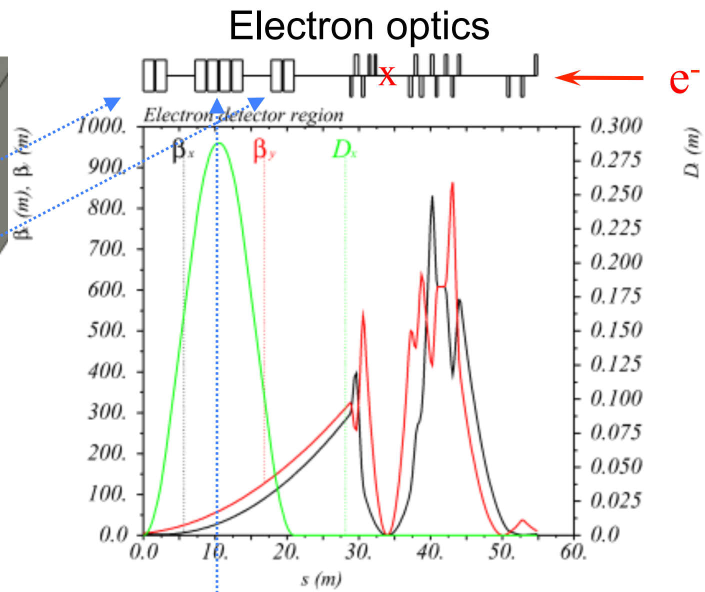
- Recoils in exclusive (diffractive) processes
  - Recoil baryons
    - *Large t (p_T) range and good resolution desirable*
  - Coherent nuclear processes
    - *Good small-p_T acceptance extends detectable mass range*
    - *Suppression of incoherent background for heaviest nuclei through detection of all fragments and photons*
- Partonic fragmentation in SIDIS
  - Correlations of current and target jets
  - Decays of strange and charmed baryons
- Nuclear spectators and fragments
  - Spectator tagging with polarized light ions
    - *p_T resolution < Fermi momentum*
  - Final state in heavy-ion reactions
    - *Centrality of collision (hadronization, shadowing, saturation, etc)*
- Heavy flavor photoproduction (low-Q^2 electron tagging)



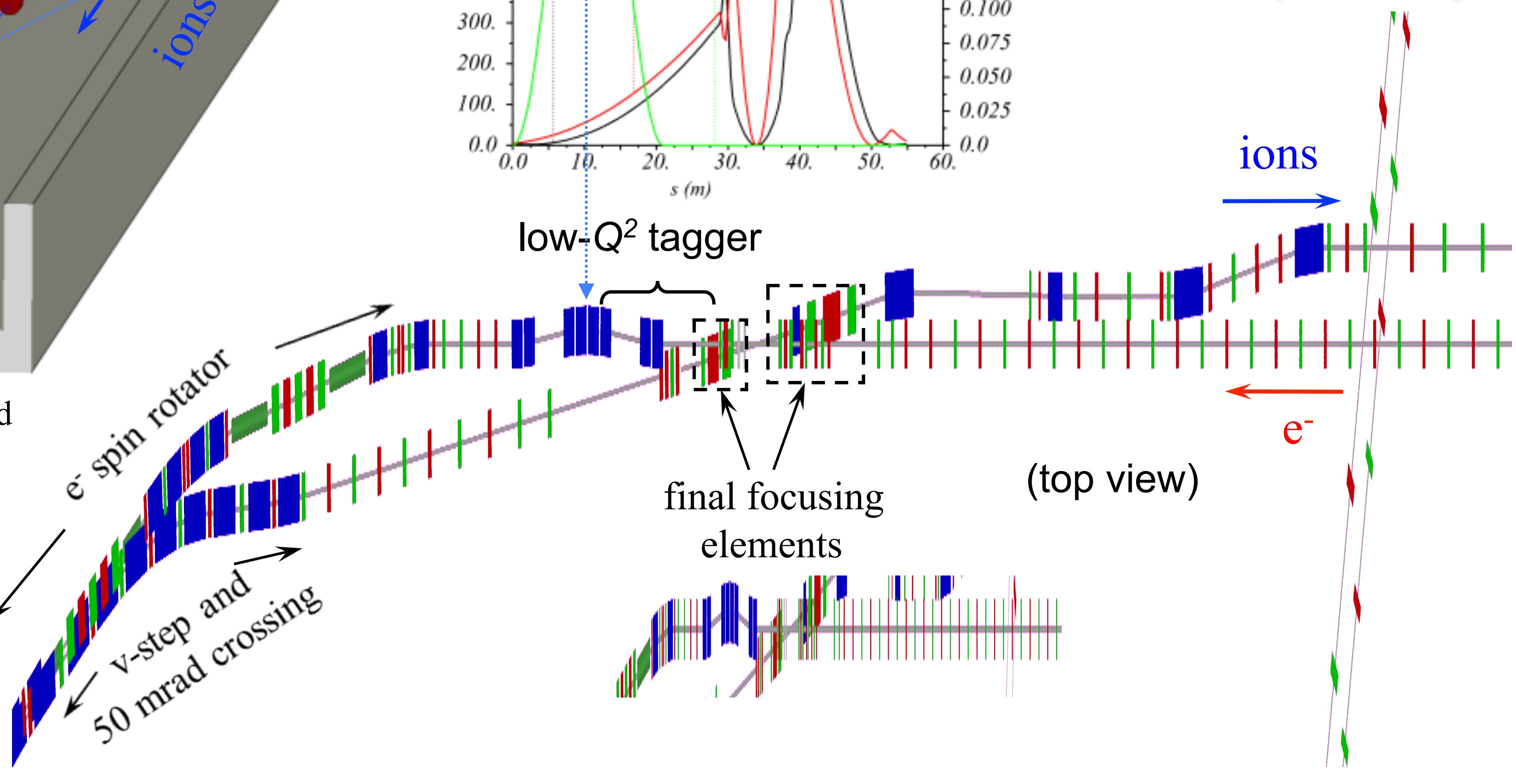
Low-Q^2 electron tagger



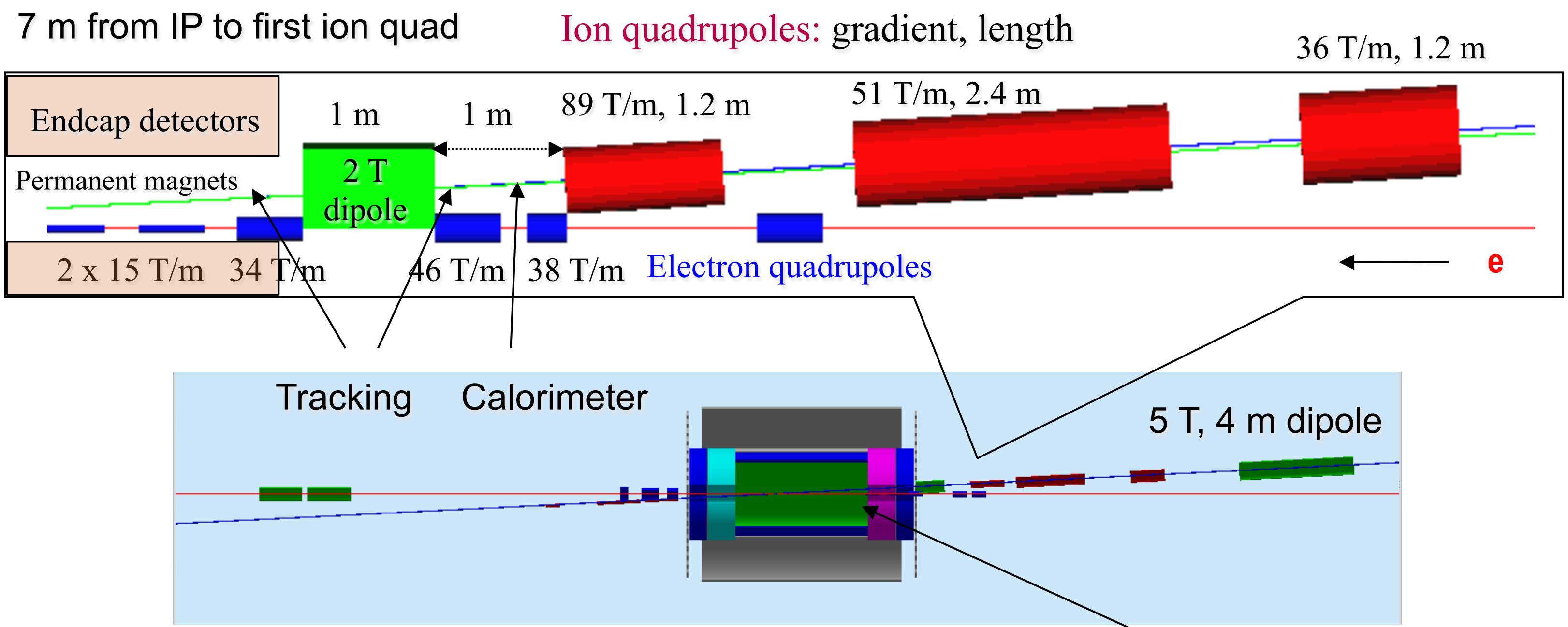
Electron beam aligned with solenoid axis

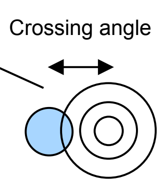


The tagger chicane could also be used for a Compton polarimeter. The tagger and the space from IP to tagger can be instrumented for luminosity monitoring.



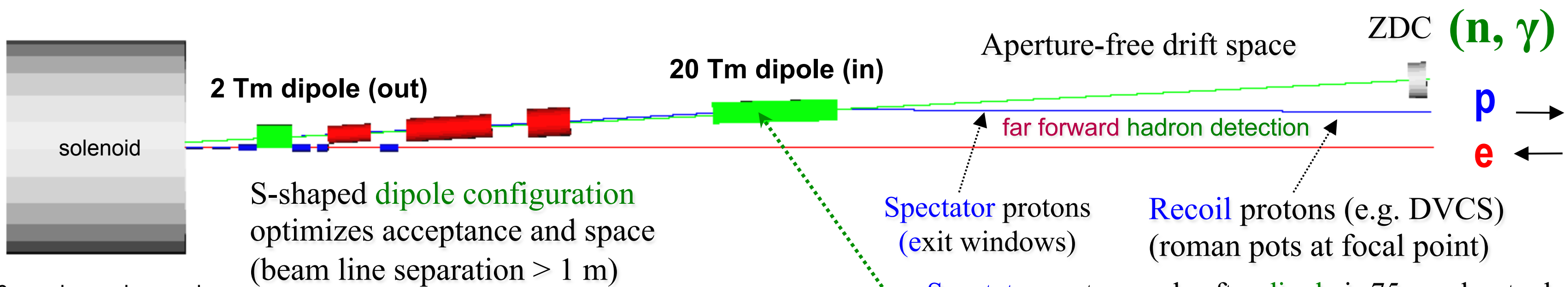
Forward detection *before* ion quads





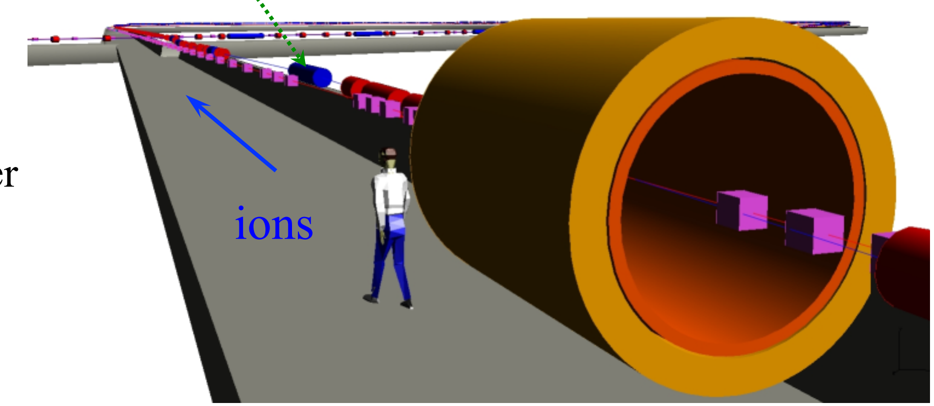
- 50 mrad crossing angle
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs
- Dipole before quadrupoles further improves resolution in the few-degree range
- Low-gradient quadrupoles allow large apertures for detection of *all* ion fragments
  - **Peak field** = quad **gradient** x aperture **radius**

Forward detection *after* ion quads



50 mrad crossing angle
(Belle II: 83 mrad)

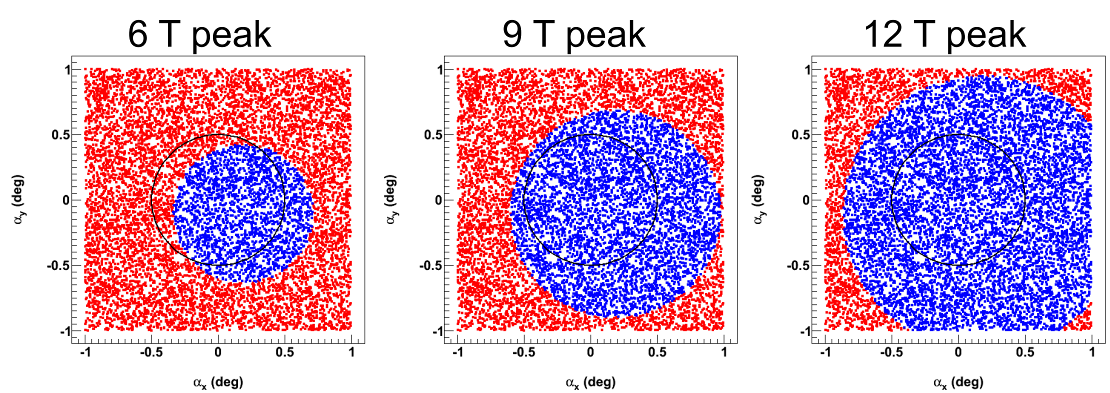
Spectator proton angle after dipole is 75 mrad wrt p beam



- S-shaped transport optimizes acceptance for both neutrals and charged particles.
- Lots of space for Zero-Degree Calorimeter (ZDC) on the outside of the ring
  - EMcal and CERN RD52 "DREAM" or particle flow Hcal (~30%/√E)
- Quad acceptance for neutrals depends on **peak field** (6 T baseline), but in 1-2° range.

Red: **neutrals** detected *before* ion quadrupoles

Blue: **neutrals** detected *after* ion quadrupoles



Far-forward detection summary

- Good acceptance for *all* ion fragments – *rigidity different from beam*
  - **Large magnet apertures** (*i.e.*, small gradients at a fixed maximum peak field)
  - *Roman pots not needed for spectators and high-p_T fragments*
- Good acceptance for low-p_T recoils – *rigidity similar to beam*
  - **Small beam size** at detection point (downstream focus, efficient cooling)
  - **Large dispersion** (generated *after* the IP, D = D' = 0 at the IP)
  - With a 10σ beam size cut, the low-p_T recoil proton acceptance at the MEIC is:

    Energy: up to **99.5%** of the beam for *all angles*

    Angular (*θ*): down to **2 mrad** for *all energies*
- Good momentum- and angular resolution
  - Should be limited only by initial state (beam). At the MEIC:

    Longitudinal (dp/p): 4×10^{-4}

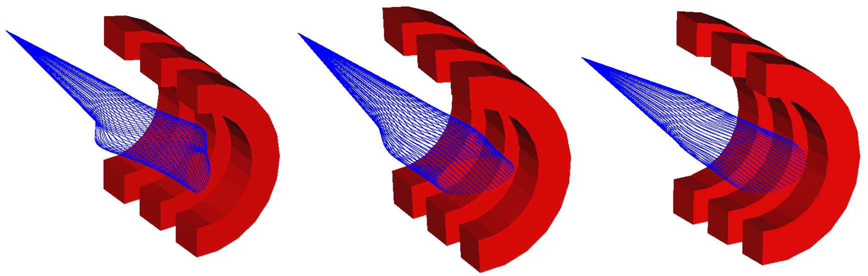
    Angular (θ, for all φ): 0.2 mrad

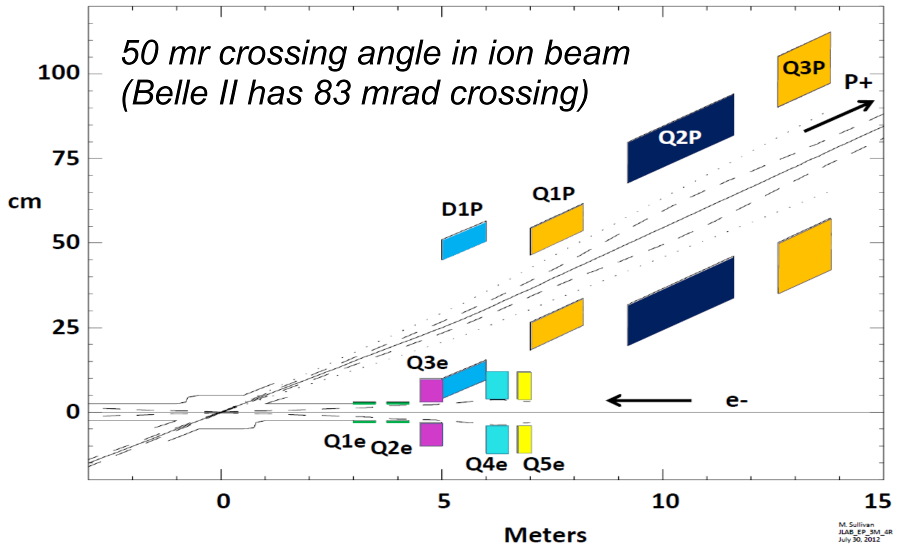
    ~15 MeV/c resolution for a tagged 50 GeV/A deuterium beam!
  - Long, instrumented drift space (no apertures, magnets, etc)
- Sufficient beam line separation (~ 1 m)

Fragment acceptance

proton-rich fragments
"spectator protons from ^{2}H"

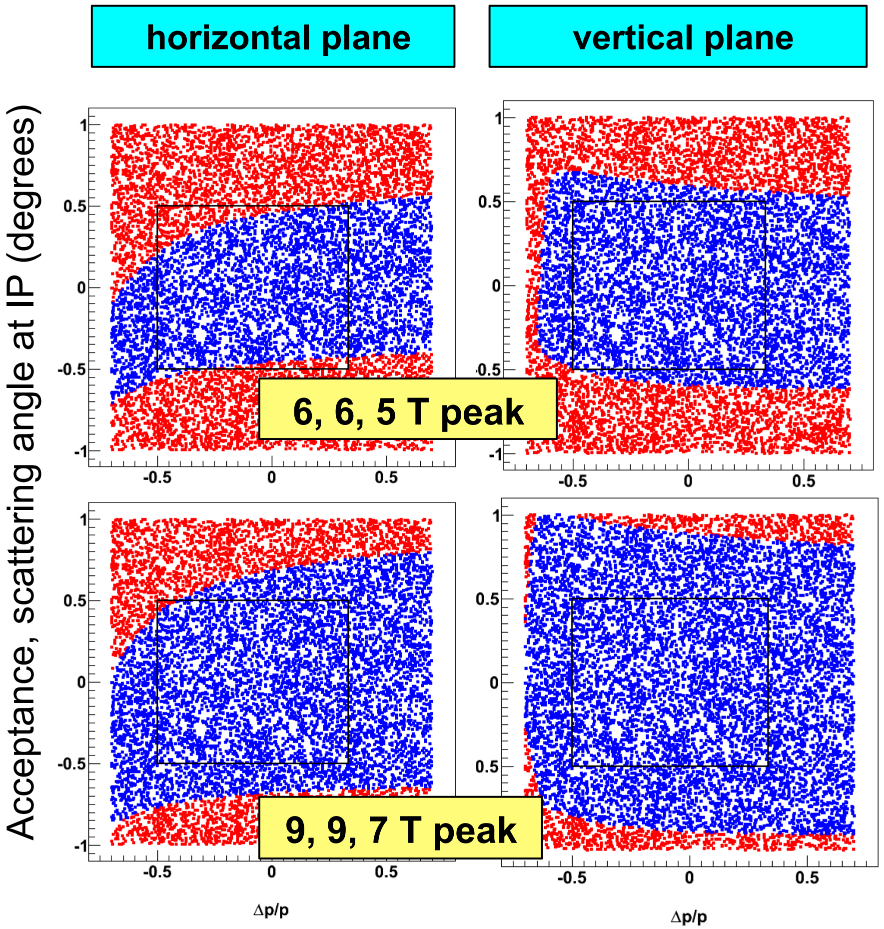
neutron-rich fragments
"tritons from N=Z nuclei"





- Baseline: Q1p and Q2p with 6 T peak fields

Forward acceptance vs.magnetic rigidity

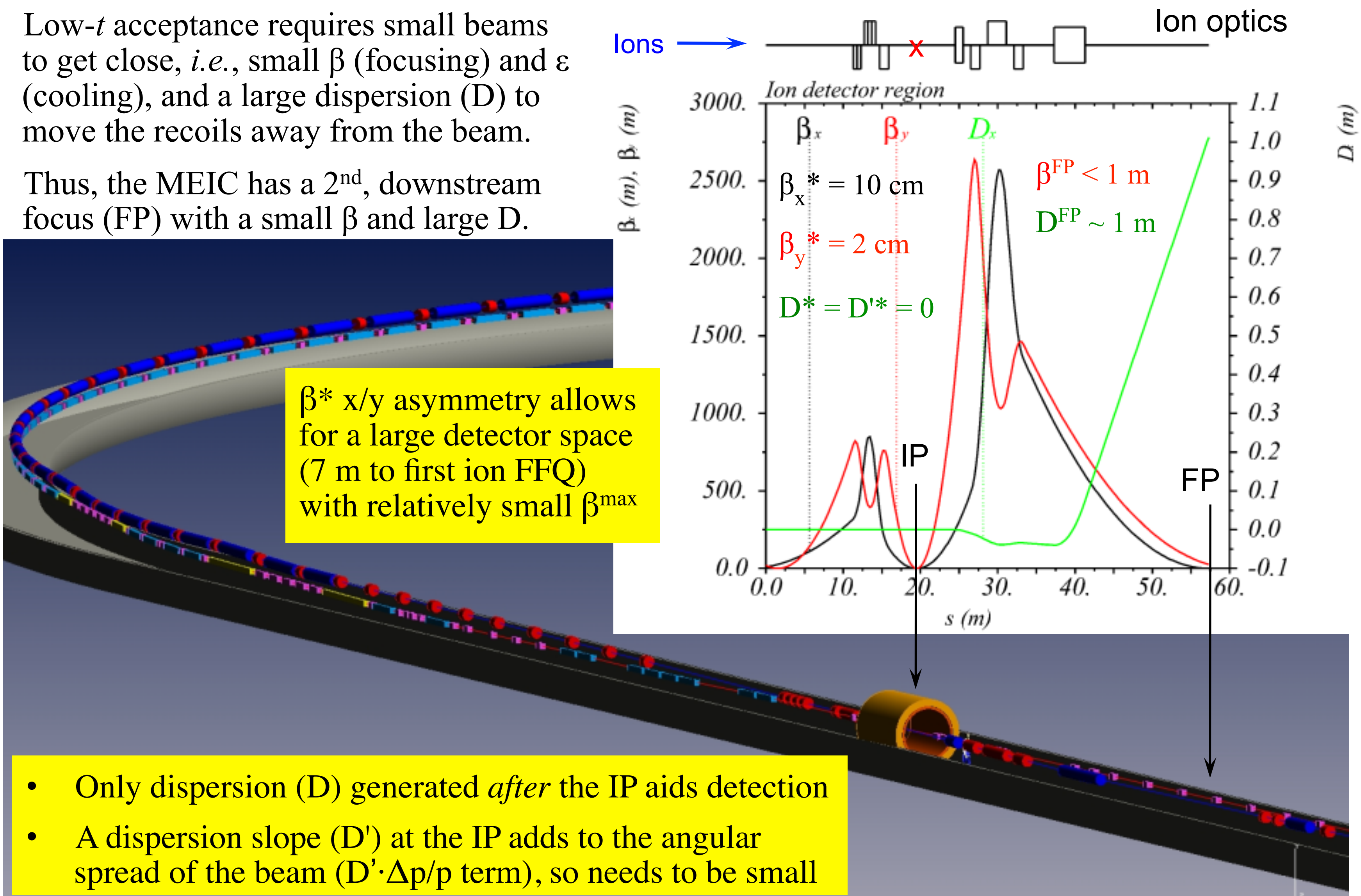


Red: Detection *before* ion quadrupoles

Blue: Detection *after* ion quadrupoles

Low-t (p_T) recoil baryon acceptance

- Low-*t* acceptance requires small beams to get close, *i.e.*, small β (focusing) and ε (cooling), and a large dispersion (D) to move the recoils away from the beam.
- Thus, the MEIC has a 2nd, downstream focus (FP) with a small β and large D.



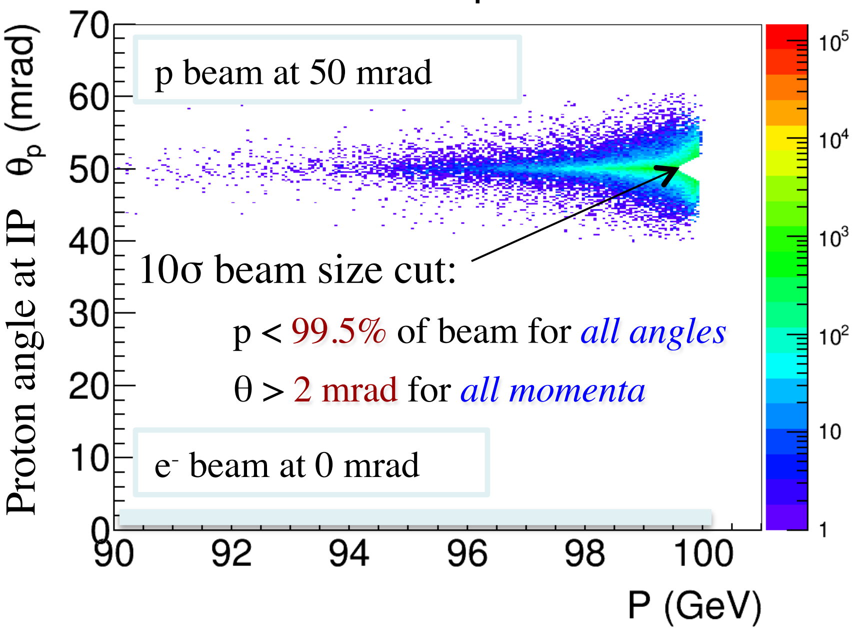
β* x/y asymmetry allows for a large detector space (7 m to first ion FFQ) with relatively small β^{max}

- Only dispersion (D) generated *after* the IP aids detection
- A dispersion slope (D') at the IP adds to the angular spread of the beam (D'·Δp/p term), so needs to be small

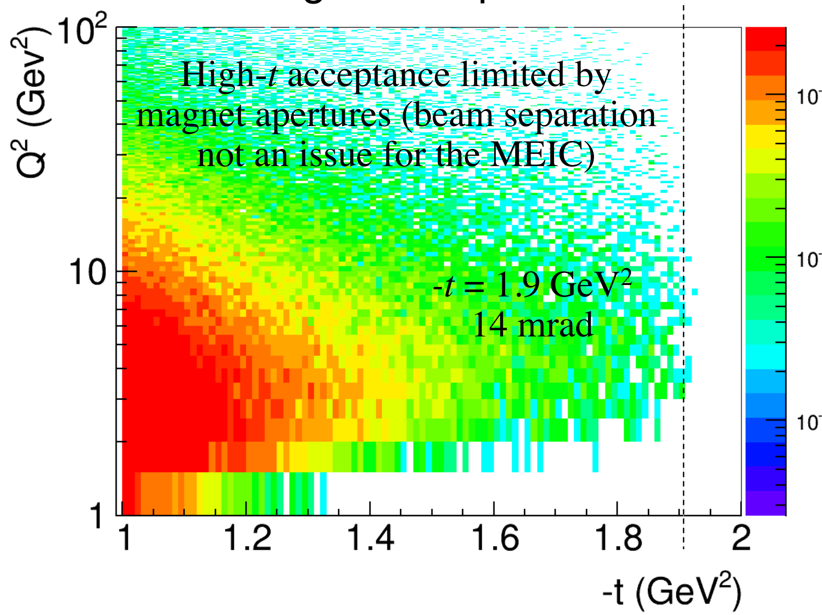
DVCS recoil proton acceptance

- **Kinematics:** 5 GeV e^- on 100 GeV p at a crossing angle of 50 mrad.
  - Cuts: $Q^2 > 1$ GeV^2, $x < 0.1$, $E'_e > 1$ GeV, recoil proton 10σ outside of beam
- **DVCS generator:** MILOU (from HERA, courtesy of BNL)
- **GEANT4 simulation:** tracking through all magnets done using the JLab GEMC package

low-*t* acceptance



high-*t* acceptance



- Recoil proton angle is independent of electron beam energy: $\theta_p \approx p_T/E_p \approx \sqrt{(-t)}/E_p$
- The wide angular distribution at E_p = 100 GeV makes precise tracking easier

Bunch spacing and identification

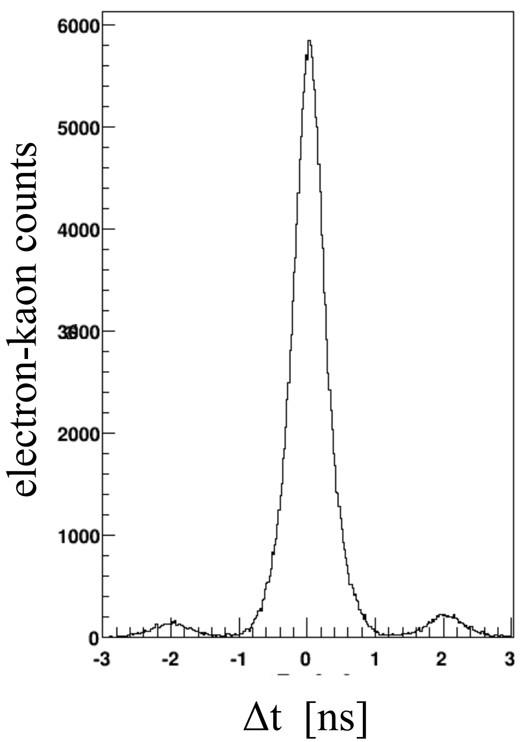
- Existing detectors (CLAS, BaBar, etc) at machines with high bunch crossing rates have not had problems in associating tracks with a specific bunch.

- Example: CLAS detector at JLab 6 GeV
  - 2 ns bunch spacing (500 MHz rep. rate)
  - 0.2 ns TOF resolution (0.5 ns FWHM)
  - The figure shows time matching of kaons in CLAS with electrons in the (low-Q^2) tagger, in turn matched to the accelerator RF signal

    The 2 ns bunch structure is clearly resolved
  - CLAS12 aims at a TOF resolution of 80 ps

- The bunch spacing in the MEIC is similar to CLAS and most e^+e^- colliders
  - PEP-II/BaBar, KEKB/Belle: **8 ns**
  - Super KEKB/Belle II: **4 ns** *(2 ns with all RF buckets full)*
  - MEIC: **1.3 ns** [750 MHz]
  - CERN Linear Collider (CLIC): **0.5 ns** [2 GHz]

K-e coincidence time in CLAS 6 GeV data



Instantaneous rates

- For a given luminosity, increasing the crossing rate reduces the number of collisions per crossing, making it easier to resolve individual events.
  - Note that the *average collision rate* does not depend on the bunch structure
- The number of collisions per crossing in the MEIC is comparable to HERA.

Events (e-p collisions) per bunch crossing	1.33 ns spacing (MEIC)	133 ns spacing (~HERA)
DIS @ $L=10^{34}$	10^{-3}	10^{-1}
photo @ $L=10^{34}$	10^{-1}	10
DIS @ $L=10^{32}$	10^{-5}	10^{-3}
photo @ $L=10^{32}$	10^{-3}	10^{-1}

Order-of-magnitude estimates of the instantaneous DIS and photoproduction rates based on a 7.5 mb total e-p cross section.

- Event spacing is particularly important for time matching of tracks in the central and far-forward detectors.
  - Only the former pass the vertex tracker
  - Photoproduction events also give rise to hadrons at small angles.
- Matching is further improved by good resolution in the far-forward detectors.
  - Angular for path-length corrections
  - Momentum for β corrections
  - Timing < 1 ns

Asynchronous trigger

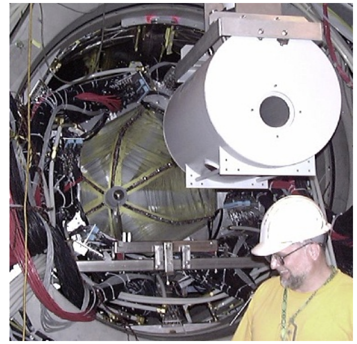
- The MEIC will use a "smart" asynchronous trigger and pipelined electronics
  - The MEIC L1 rate is expected to be comparable to GlueX (200 kHz)
    - *Low-Q^2 (photoproduction) events will be pre-scaled*
  - Simple tracking at L2 will suppress random background (not from vertex)
    - *Already planned for CLAS12*

- Data-driven, asynchronous triggers are well-established
  - If the number of collisions of interest per bunch crossing is << 1, synchronizing the trigger to each RF clock cycle becomes inefficient
  - Sampling rate requirements for the pipelined electronics depend on signal properties and backgrounds, not the bunch crossing frequency
    - *JLab 12 GeV uses flash ADCs with 250 MHz (4 ns) sampling*
  - When a trigger condition is fulfilled (*e.g.*, e^- found), memory buffers are written to disk or passed to L3 (at PANDA signals will go directly to L3)
  - Correlations with the RF are made offline
  - T0 is obtained from tracking high-β particles (*e.g.*, electrons in CLAS)

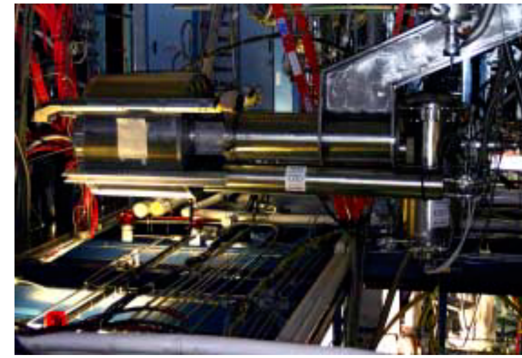
Generic detector R&D – an example

- As part of the R&D program, a new, permanent facility for tests of photosensors in high magnetic fields is being set up at JLab
  - Two 5T magnets provided by JLab
- MCP-PMTs (or LAPPDs) with small pore size (2-10 μm) could provide a radiation hard, low-noise, baseline sensor suitable for single photon detection (DIRC, RICH, etc).

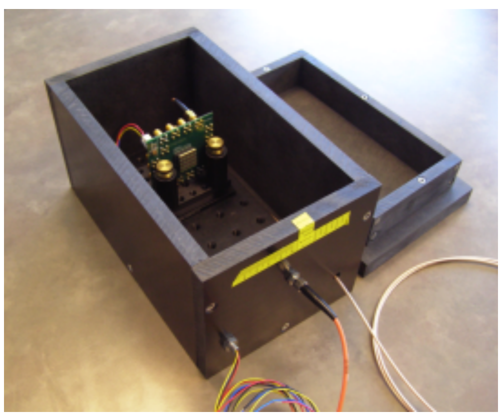
→ *talk by Tom Ludlam*



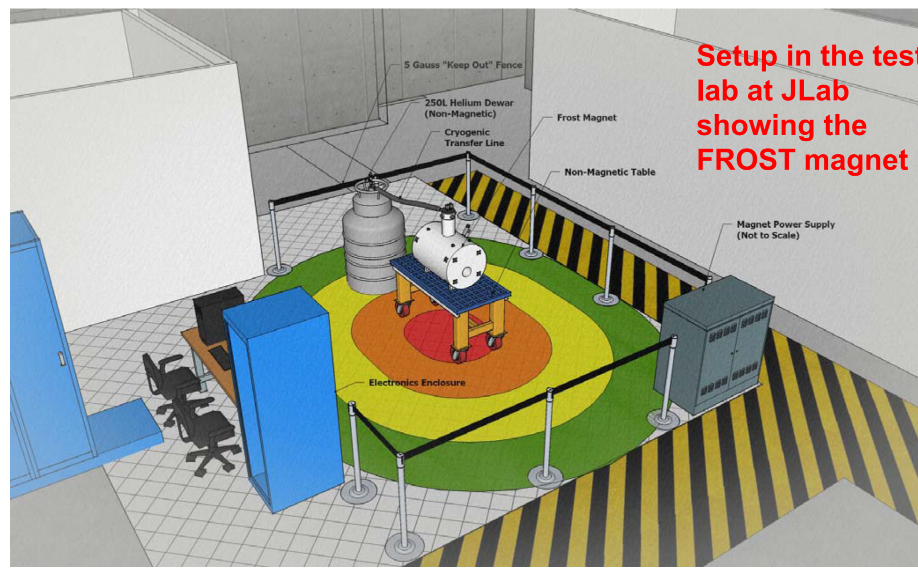
CLAS FROST solenoid with 5” bore



CLAS DVCS solenoid with 9” bore



Non-magnetic dark box with pulsed LED for the DVCS solenoid – note the GlueX SiPM (Hamamatsu S11064-050P(X))



Participation in R&D program

Listed below are institutions participating in the detector R&D program that also have a strong involvement at JLab

- Many R&D proposals are collaborative (BNL/JLab/users)

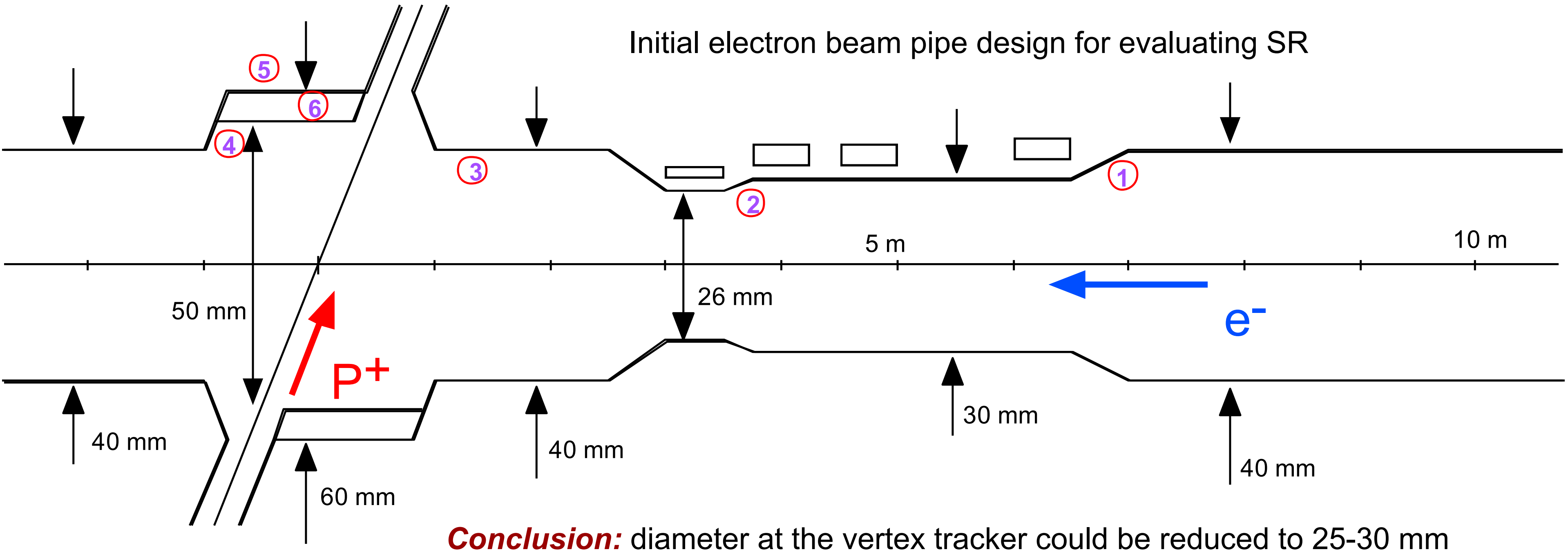
- Catholic University of America
- CEA, Saclay, France
- College of William and Mary
- INFN, Italy
- Mississippi State University
- Old Dominion University
- Temple University
- Universidad Técnica Federico Santa María, Chile
- University of South Carolina
- University of Virginia

Summary and Outlook

- The full-acceptance detector is a cornerstone of the MEIC design, offering unprecedented acceptance and resolution
- Integration of the detector and extended interaction region with the accelerator has been the main priority
- Focus is currently shifting towards more detailed simulations of the central detector
- Lots of opportunities for collaboration on detector R&D
  - Generic Detector R&D for an EIC program

Backup

Synchrotron radiation background



Conclusion: diameter at the vertex tracker could be reduced to 25-30 mm

Surface:	1	2	3	4	5	6
Power (W) @ 5 GeV	3.0	5.7	0.2	0.8	-	0.03
γ >10 keV @ 5GeV	5.6×10^5	3.4×10^5	1.4×10^4	5.8×10^4	167	3,538
Power (W) @ 11 GeV	4.2	8.0	0.3	1.1	-	0.04
γ >10 keV @ 11 GeV	5.6×10^5	2.8×10^5	9.0×10^4	3.8×10^5	271	13,323

Photon numbers are per bunch

Simulation by M. Sullivan (SLAC)

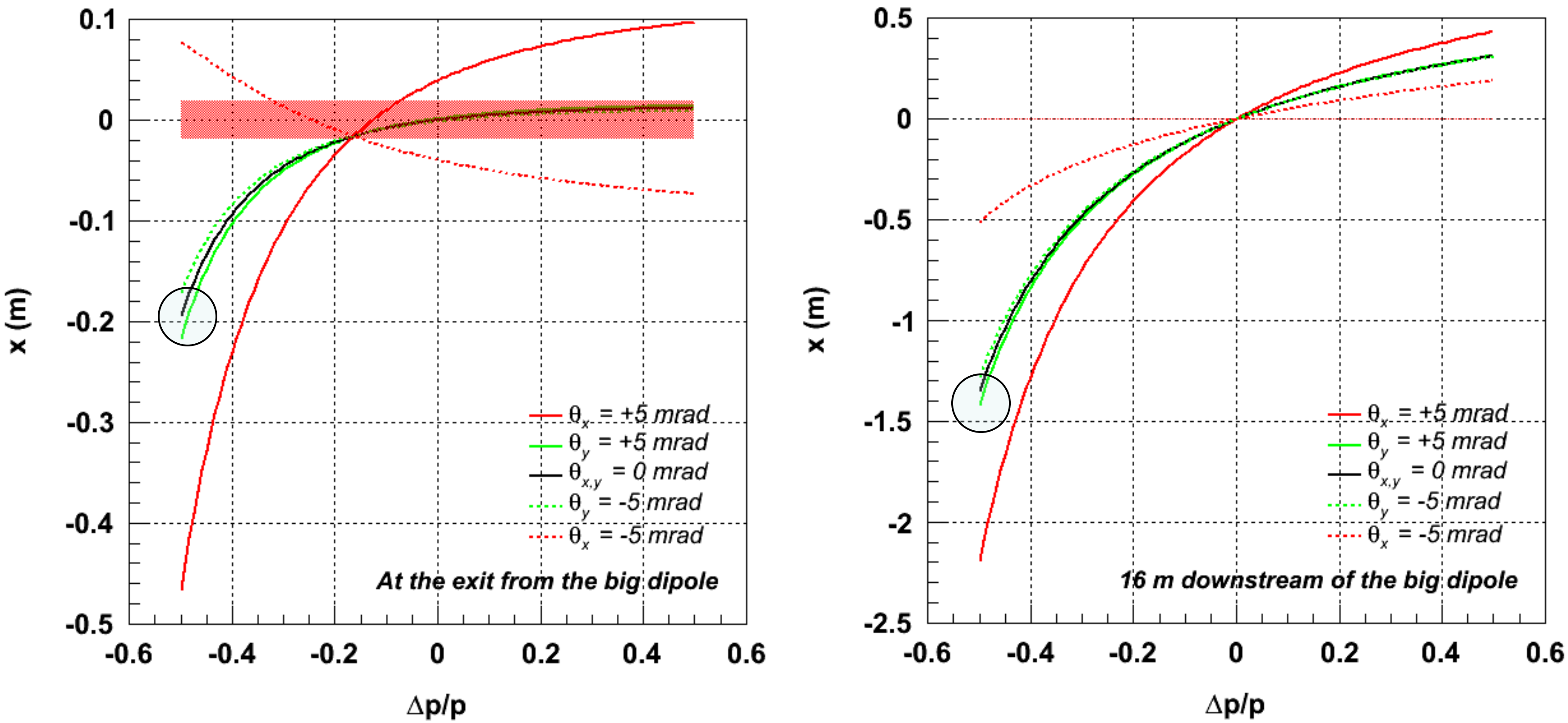
Hadronic backgrounds

- Random hadronic background
  - Assumed to be dominated by scattering of beam ions on residual gas (mainly ^{2}H) in the beam pipe between the ion exit arc and the detector.
  - Correlated background from photoproduction events is discussed separately

- The conditions at the MEIC compare favorably with HERA
  - Typical values of *s* are 4,000 GeV^2 at the MEIC and 100,000 GeV^2 at HERA
  - Distance from arc to detector: 65 m / 120 m = 0.54
  - p-p cross section ratio σ(100 GeV) / σ(920 GeV) < 0.8
  - Average hadron multiplicity per collision $(4000 / 100000)^{1/4} = 0.45$
  - Proton beam current ratio: 0.5 A / 0.1 A= 5
  - At the *same vacuum* the MEIC background is 0.54 * 0.8 * 0.45 * 5 = 0.97 of HERA
  - But MEIC vacuum should be closer to LHC (10^{-10} torr) than HERA (10^{-7} torr)

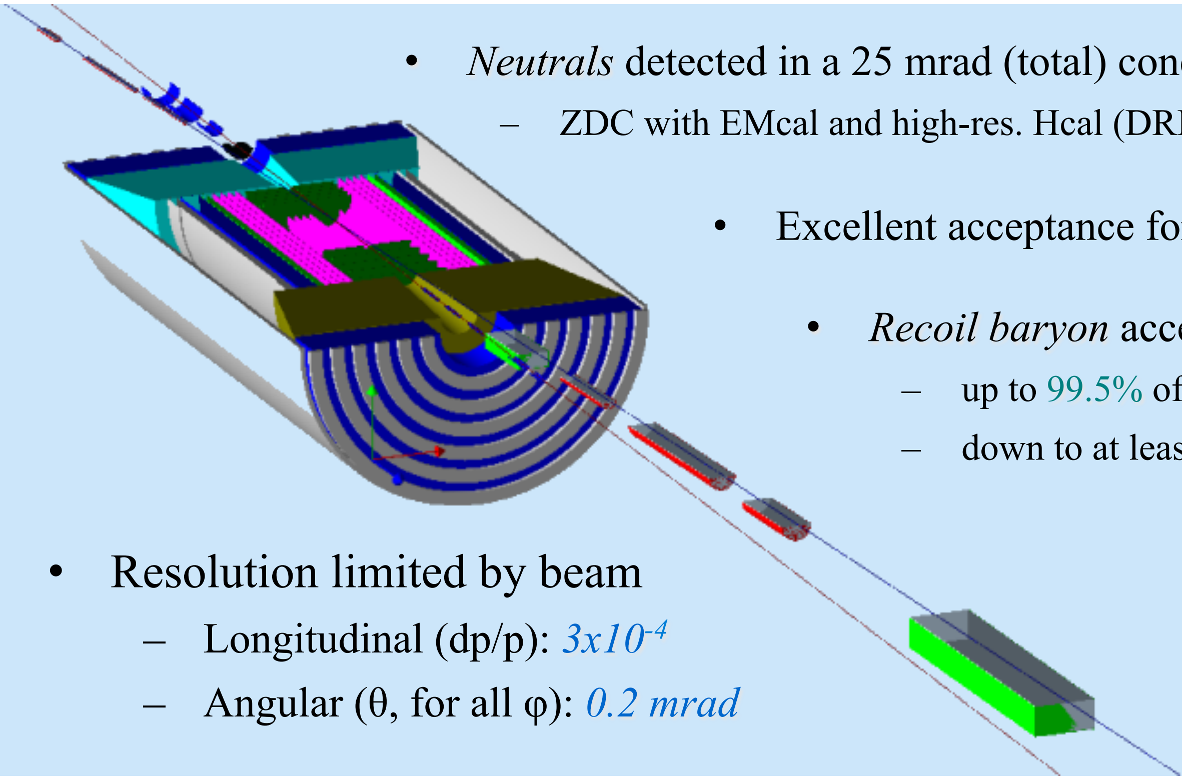
- The signal-to-background ratio will be even better
  - HERA luminosity reached ~ 5×10^{31} $cm^{-2}s^{-1}$
  - The EIC (and the MEIC in particular) aims to be close to 10^{34} $cm^{-2}s^{-1}$

Spectator angles *after* dipole

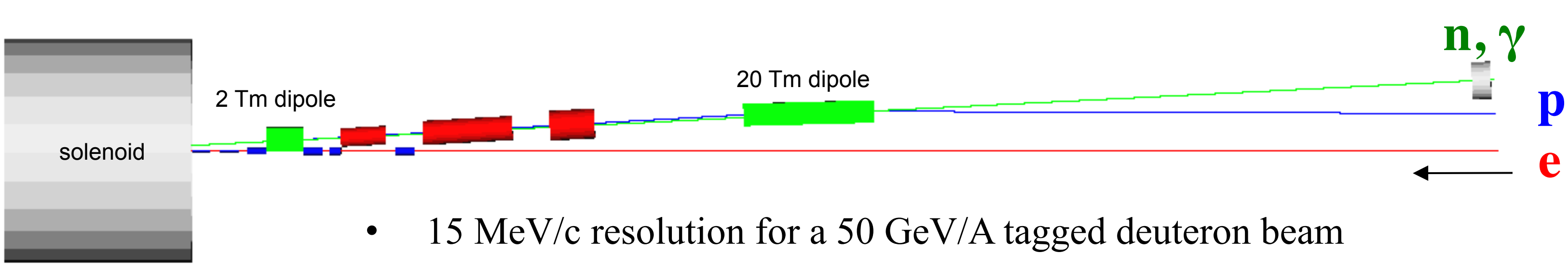


- True spectator fragments have very small scattering angles at the IP (black curve)
- Spectator protons from deuterium have $\Delta p/p = -0.5$
- After passing the large bending dipole, the spectator angle with respect to the ion beam is large
- The angle in the magnet-free drift section after the dipole can be calculated from the displacement at the dipole exit and a point 16 m further downstream:
  - θ = atan ((1.4- 0.2)/16) = 75 mrad (= 4.3°)

Far-forward detection summary



- *Neutrals* detected in a 25 mrad (total) cone *down to zero degrees*
  - ZDC with EMcal and high-res. Hcal (DREAM or particle flow).
- Excellent acceptance for *all ion fragments*
- *Recoil baryon* acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to at least 2-3 mrad for *all momenta*
- Resolution limited by beam
  - Longitudinal (dp/p): $3x10^{-4}$
  - Angular (θ, for all φ): *0.2 mrad*



- 15 MeV/c resolution for a 50 GeV/A tagged deuteron beam